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Case studies of early warning system of unstable slopes using tilting sensor array

Études de cas du système d'alerte précoce des pentes instables utilisant un réseau de capteurs d'inclinaison

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ABSTRACT: Many large-scale sediment disasters result in the destruction of infrastructure and loss of human life. The mitigation of vulnerability to slope and landslide hazards will benefit significantly from early warning alerts. The authors have been developing monitoring technology that uses a Micro Electro Mechanical Systems (MEMS) tilt sensor array that detects the precursory movement of vulnerable slopes and informs the issuance of emergency caution and warning alerts. In this regard, the determination of alarm thresholds is very important. Although previous studies have investigated the recording of threshold values by an extensometer which installation of an extensometer at appropriate sites is also difficult. The authors prefer tilt sensors and have proposed a novel threshold for the tilt angle, which was validated in this study. This threshold has an interesting similarity to previously reported viscous models. Additionally, multi-point monitoring has recently emerged and allows for many sensors to be deployed at vulnerable slopes without disregarding the slope's precursory local behaviour. With this new technology, the detailed spatial and temporal variation of the behaviour of vulnerable slopes can be determined as the displacement proceeds toward failure.

RÉSU-MÉ : De nombreuses catastrophes causées par le déplacement de sédiments à grande échelle peuvent entraîner la destruc-tion d'infrastructures et à la perte de vies humaines. Une alerte précoce aux pentes vulnérables et aux glissementsde terrain donnée aux mo-ments adéquats contribuera considérablement à maîtriser ces mauvaises retombées. Les auteurs de cette étude ont développé une technolo-gie de surveillance qui utilise une série de capteurs d'inclinaison du Système micro électromécanique (MEMS) qui détecte le mouvement précurseur de pentes vulnérables et l'informe par l'émission d'avertissements d'urgence ou d'alertes de danger. À cet égard, la détermina-tion des seuils de déclanchement des alarmes est très importante. Malgré l'étude préalablement effectuée sur des valeurs de seuil enregis-trées par un extensomètre, l'installation d'extensomètre sur le site approprié est également difficile. Les auteurs préfèrent le capteur d'inclinai-son et ont proposé pour le nouveau seuil l'angle d'inclinaison, qui a été d'ailleurs rendu valable dans cette étude. Ce seuil présente une simili-tude intéressante avec les modèles visqueux précédemment rapportés.

KEYWORDS: landslide, slope failure, monitoring, early warning, MEMS tilting sensor.

1 INTRODUCTION

Slope monitoring has a long history of practice for landslides that move slowly over months or years until final failure and produce head scarps and cracks in the meantime. Through its extensive application, slope monitoring has become capable of defining the range of moving soil mass. The extensometer, which is installed across well-defined cracks and other displacement discontinuities, is extensively used for monitoring slow-displacement slopes. Saito et al., (1965) and Fukuzono et al. (1985) have proposed an important method for predicting the time of slope failure. Recently, the idea of displacement monitoring using GPS, LiDAR, and InSAR has been introduced (Casagli et al., 2010; Kayen et al. 2006; Yin et al., 2010). The authors' opinion on these technologies is that the high cost of the extensometer may prevent its use when funding is insufficient. Additionally, the above-mentioned technologies may not be able to achieve the required accuracy when very small slope displacement plays a major role in the issuance of warnings. The latter concern will be discussed later in this paper.

Slope movement may occur faster, and only a few days or even hours may elapse until failure. This is particularly the case with rainfall-induced landslides on which the authors are focusing. The limited time preceding the failure makes the use of LiDAR and InSAR very difficult. The displacement of slopes receiving heavy rain is very small and has limited size before failure. Therefore, GPS and InSAR cannot capture the movement. Moreover, the extensometer may not be suitable when the range of instability is unknown and large displacement occurs suddenly, as is the case of rainfall-induced landslides. Because of these problems, the authors (Uchimura et al., 2015) have proposed a different slope monitoring and early warning approach, some case studies shown in this paper will further proove the early warning method is usefull for slope failure and landslide.

2 MEMS TILT SENSOR FOR MONITORING OF VULNERABLE SLOPES

The authors have been developing a new type of slope monitoring device with the objective of predicting the time of failure triggered by heavy rainfall (Uchimura et al., 2015). The major issues in the development of this technology is the use of Micro Electro Mechanical Systems (MEMS) sensors for the tilting angle, which is attached on the top of a steel rod embedded in a slope (Figures 1 and 2) and precisely measures the inclination (rotation) angle of the rod when it is pushed laterally by the slope's moving surface soil. Because rainfall-induced slope failure occurs within several hours after a precipitation event, where there is no pre-existing deformation or cracks, the traditional methods of the extensometer, LiDAR, and so on, are not helpful. Because MEMS sensors are less expensive, many sensors can be deployed over the investigated slope. The monitoring data are sent to the office through a wireless network and interpreted. To date, MEMS tilt sensors have been deployed at more than 100 sites, both domestically and internationally (Japan, Australia, China, Taiwan, and a few more countries). The threshold for issuing an early warning is specified as the rate of inclination equal to 0.1°/hour (Uchimura et al., 2015).

3 VALIDATION OF TILT SENSOR FOR SLOPE MONITORING

Previously, MEMS tilt sensors have been used at more than 100 sites with slope instability. Most of these slopes did not failure, but several of these slopes have failured with and without rainfall and provided important data. Based on these data, the warning threshold has been determined as 0.1°/hour. In this section, various cases that have not been reported are discussed.

3 .1 *Prevention of secondary disaster during restoration of failed slope – Fukuoka pref., Japan*

An EWS was successfully used in 2015 in Fukuoka Prefecture, Japan. When this region received heavy rainfall during typhoon No. 11 "Nangka" on July 17 and 18, the slope collapsed and the local road was closed to traffic (Figure 3). This slope comprises Funi volcanic rock of andesite karst, tuff breccia, and tuff. To safely keep one lane open for traffic during slope restoration, the slope movement was monitored by a set of tilt sensors as shown in Figure 3. The traffic was intended to stop if the tilt sensor detected an excessive tilting rate during the slope restoration works.

Figure 4 shows the plot of the tilt angle and the rainfall data on July 21st and 22nd, shortly after the main slope collapse. The slope was considered to be prone to further failures during the restoration works. From 4 PM to 8 PM on July 21st, that is, immediately after the tilt sensor installation, the tilting rate of 0.083°/hour was recorded and continued until 8 AM on July 22nd. Thereafter, the tilting rate accelerated to 0.89°/hour, possibly owing to rainfall amounting to approximately 10 mm from 8 AM to 9 AM. Furthermore, owing to further rainfall after 11 AM, the tilting rate sharply increased to 12°/hour after 12 PM and the slope finally collapsed at 12:30 PM. Thus, the field monitoring helped control the traffic during the critical period and ensured the safety of human life.

3 .2 *A case of detection of rain induced landslides in critical slopes the Lake Baroon Catchment, Maleny plateau, Brisbane, Australia*

The Landers Shute Water Treatment Plant (LSWTP), sourced from the Baroon Pocket Dam (BPD), supplies the Sunshine Coast with 50-120 ML/day of water. This Dam is vital for potable water production in South East Queensland. Additionally, SEQWater has committed to a potential 300-year lifespan for the Dam. Moreover, SEQWater considers steep and unstable slopes as "Extreme Uncontrolled Risks" to the LSWTP. The investigated area is the Lake Baroon catchment in Maleny (Figure 5), and is located approximately 100 km north of Brisbane (26.76 0S 152.85 0E). The Mapleton-Maleny Plateau, wherein the Lake Baroon catchment is located, has been documented and discussed since the mid-1950s as an area that is highly susceptible to rainfall-induced slope failure. Additionally,

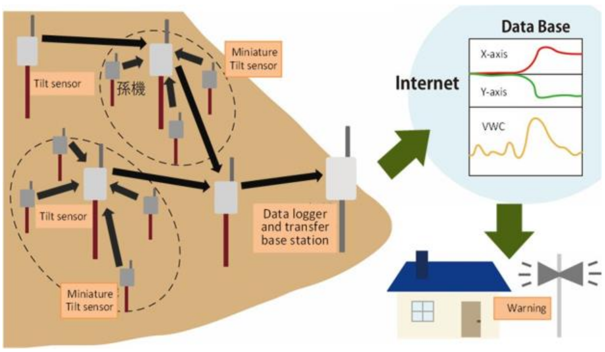

Figure 1. An early warning system of slope failure by multi-point tilt and volumetric water content

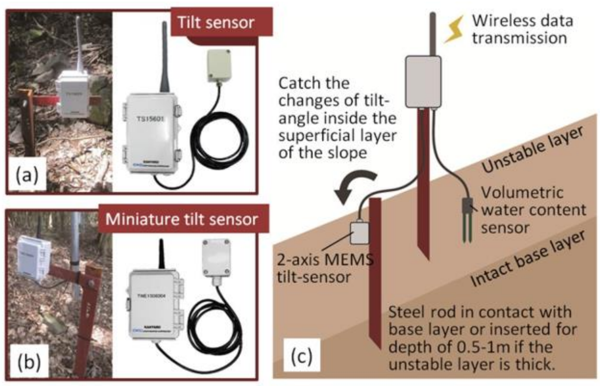

Figure 2. Schematic illustration of MEMS tiltometer sensor for early warning

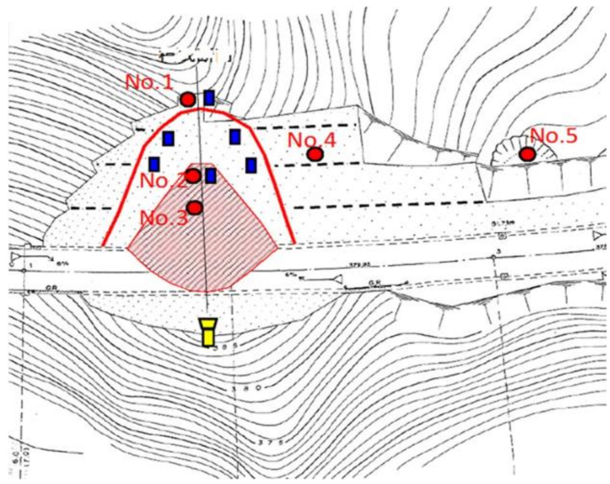

Figure 3. Monitored slope in Fukuoka.

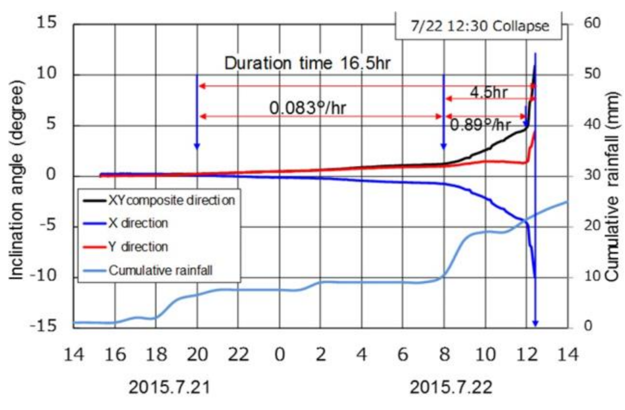

Figure 4. Time histories of monitored data at Fukuoka site.

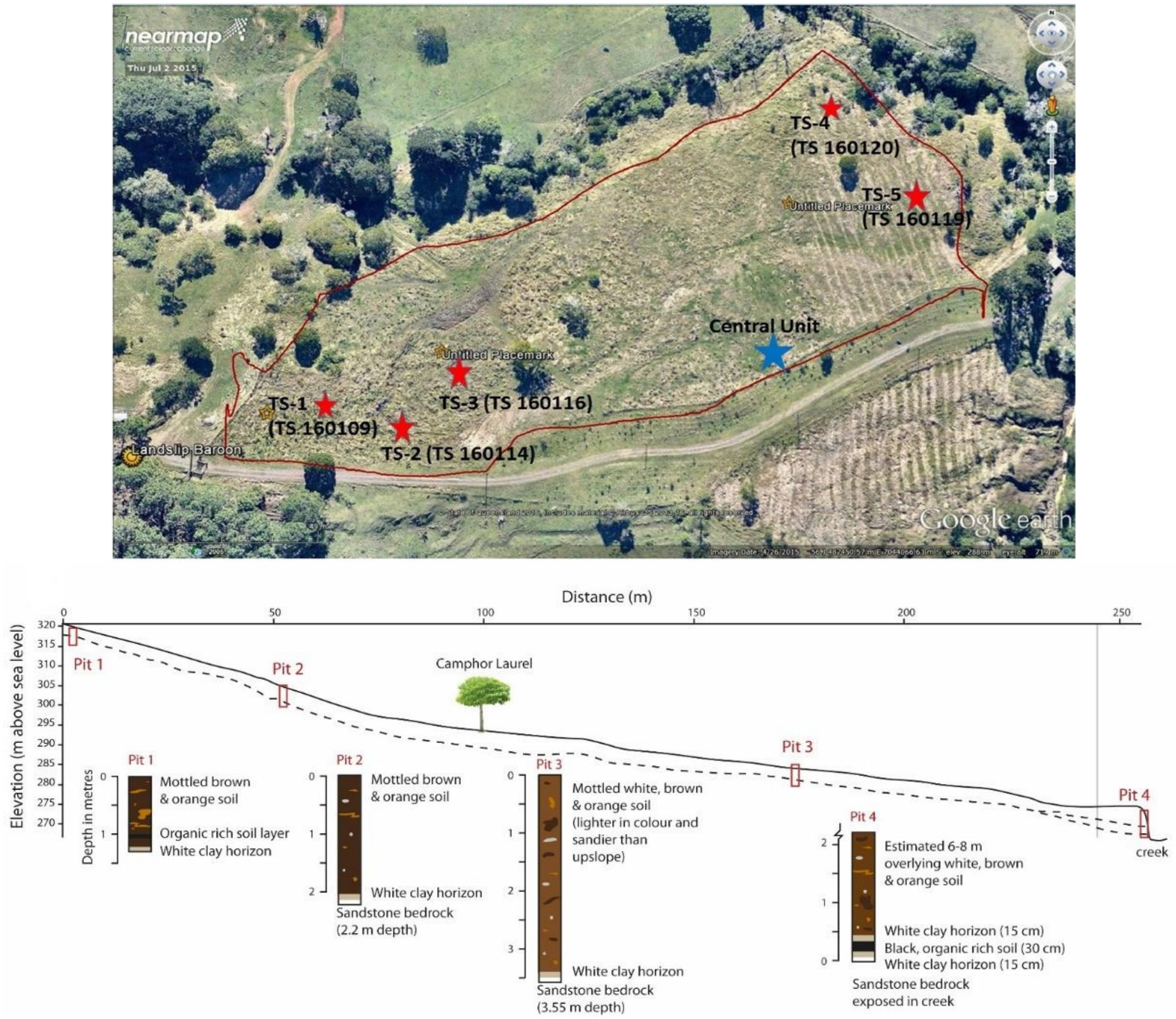

Figure 5. (a) Locations of the sensors. X denotes the local downslope direction, whereas Y denotes the direction perpendicular to downslope. (b) Cross-section from the above GPR profile, showing the position of the white clay/bedrock reflector (dashed line).

the slope failure and mass movement of sediment into the waterways within the Lake Baroon catchment are recognized as a significant risk to the water quality and water storage capacity of Lake Baroon, which is used to supply water to South East Queensland. Approximately 170 mass movement landforms have been identified within the Baroon catchment, and the investigated area is one such high-risk slope. In 2008, this landslide site hosted a voluminous single-failure rotational landslide after heavy rainfall. The study employed a wide range of data collected from May 10, 2016 to 2020 to predict the slope failure under rainfall infiltration (Abeykoon et al. 2018, 2019).

This case study investigated the applicability of real-time monitoring and wireless data transmission in predicting rain-induced slope instability in critical slopes. The ground inclinometers equipped with MEMS tilt sensors, volumetric water content sensors, a rain gauge and a wireless data transmission unit (DTU) for real-time slope monitoring. The study employed a wide range of data collected in the period from 10th May 2016 to this year of 2020, for the prediction of the slope failure under rainfall infiltration.

This landslide site hosted a voluminous, single-failure rotational landslide in 2008 following heavy rainfall (Abeykoon et al.,2018). The pre-2008 landslide topography was subsequently reset by pushing failed soil and colluvium back onto the original slope. Vegetation (planting and growing trees) was suggested as an effective slope stabilization method for this area. Additionally, the five inclinometers slope monitoring experiment were installed. The real-time slope monitoring system aimed to measure the efficacy of revegetation as a slope stabilization method for this slope (Abeykoon et al. (2018)).

The real-time monitoring system that consists of five sensor units (TS1, TS2, TS3, TS4, and TS5) and a central logging station was installed in the slope as shown in Figure 5. Each sensor unit consists of a logging and transmission unit, MEMS tilt sensor, volumetric soil moisture sensor, and temperature sensor. The central unit comprises a central data logger, power supply unit (solar panel and back-up battery), data receiving unit (from sensor units), rain gauge as shown in Figure 5(a).

After characterizing the soil profile by determining the interface between soil and underlying bedrock by ground penetrating radar (GPR) survey, four locations were selected to excavate pits for determining the composition of soil layers, soil layer thicknesses and verification of GPR survey results. Figure 5(b) illustrate the longitudinal GPR profile and the GPR survey transect line and a cross-section of soil profile along the transect line with the locations of excavation pits, respectively.

The tilt angles accumulated distribution due to each rain are summarized as Figure 6, which included the accumulated distribution results in (a) 15/Jul, (b) 15/Sep, (c) 01/Oct and (d) 01/Nov of year 2016. Red means the inclinometer is tilted in the direction of the landslide slope, and blue means the inclinometer is tilted in the opposite direction of the slope.

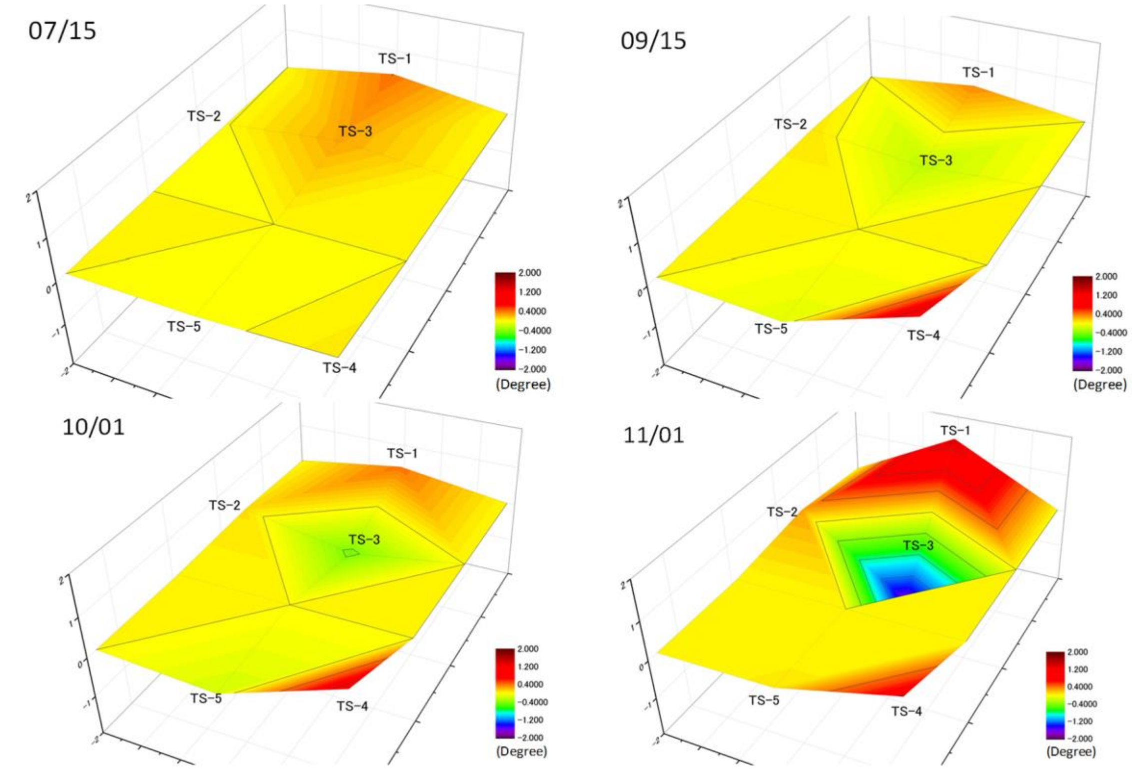

Figure 6. Distribution of accumulated inclination angle of year 2016

Figure 7. Areal view of the landslide area (28/10/2017)

Figure 8. View of the landslide area (20/02/2018)

TS1, which is located at top of the slope failed area, tilted (rotated) more than 2 degree in slope-direction during this period. TS2 which is located outside the failed area did not respond to the failure of the slope. However, TS2 started showing minor rotation with the reactivation of the failure above its location, which could be due to overloading the area of TS2 by the failed soil mass above its location. TS3, which is located at center of the slope, tilted (rotated) more than 2 degree in opposite direction of landslide slope. TS5, which is located at bottom of the landslide slope, is rotating in the direction of the slope, was pushed by the top mass of slope failure.

These results clearly show the movement of the entire slope shown in Figure 6 as time order. It can be seen that the head and the bottom of the slope are inclined in the direction of landslide slope inclination, and the middle of the slope is a circular arc slide. By arranging five sensor arrays, it is thought that false alarms can be prevented by issuing an alert based on the movement of the entire slope, instead of local fluctuations based on a single sensor result.

Figure 7 shows the aerial view of the landslide area that the photos were taken in 28/Oct/2017, and Figure 8 shows the aerial view of the landslide deformation area that the photos taken in 20/Feb/2018.These photographs show that the results correspond to the landslide collapse measured by the sensor array.

3.3 *Slope monitoring at Manzawa, Yamanashi, Japan*

The Manzawa site in Yamanashi Prefecture, Japan is situated near national road 52 and includes a large-scale reactivation of an old slope failure featuring rockfall involving the detachment and rapid downward movement of rock. Because traditional slope monitoring methods such as extensometers and borehole

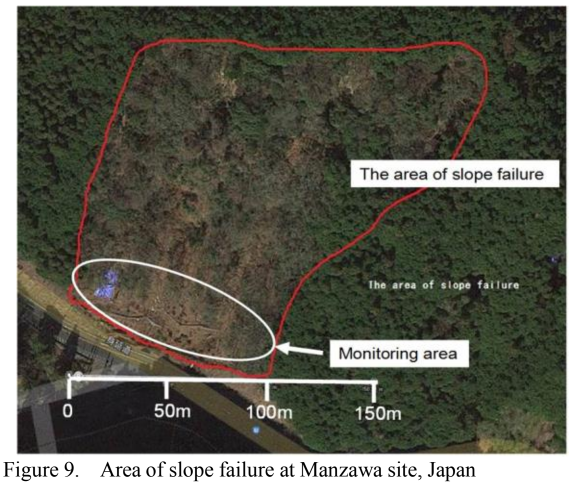

Figure 9. Area of slope failure at Manzawa site, Japan

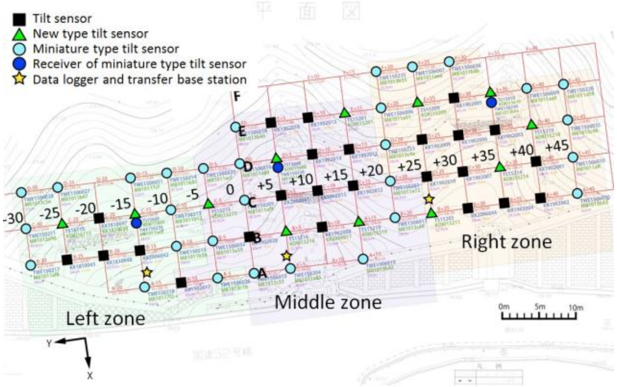

Figure 10. Arrangement of the multi-point tilt sensors

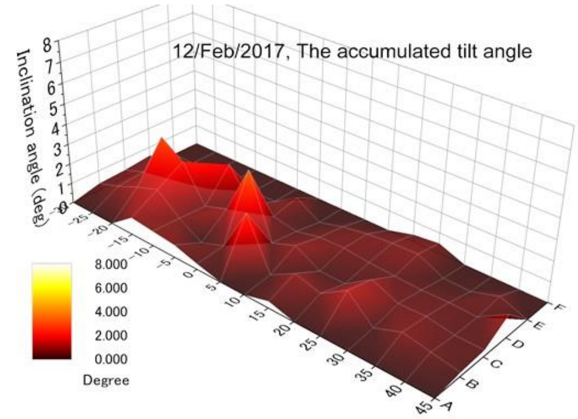

Figure 11. Distribution of accumulated tilt angle at Manzawa site.

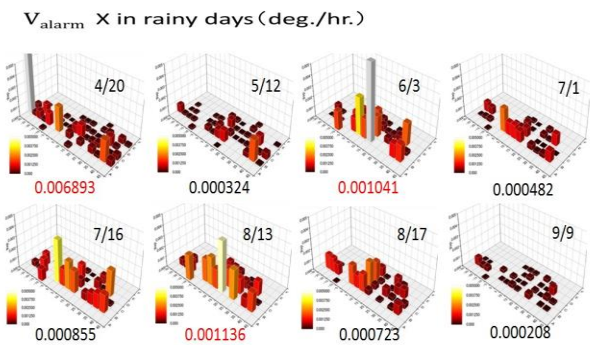

Figure 12. Distribution of tilting rates during each rainfall day at Manzawa site.

inclinometers are considered to be expensive and irrelevant to the three-dimensional monitoring of slope behaviour, multi-point monitoring using tilt sensors was attempted.

Figure 9 shows an aerial view of the Manzawa slope and Figure 10 shows the location of the multi-point tilt sensors. The spacing between the sensors was set to five meters, and 66 sensors were deployed in total. Notably, monitoring was carried out only in the lower part of the slope as shown in Figure 10, owing to administrative reasons.

The distribution of the accumulated tilt angle over the monitored area is shown in Figure 11, and its local variation is obvious. The rate of tilting during the respective precipitation events is shown in Figure 12. The precipitation events on April 20, 2017, June 3, 2017, and August 13, 2017 caused relatively higher tilting rate values, but these values did not exceed the precaution threshold of 0.01°/hour. Another issue is that higher tilting rate occurs at different points during different precipitation events, as revealed by comparing the data obtained on April 20 to those obtained on June 3 and August 13. During the two-year field validation, there was no significant change in the tilting angle, and no alert was issued. Thus, the slope was assessed as stable.

3 ASSESSMENT OF REMAINING TIME UNTIL FAILURE

3.1 *Forecast of remaining time until landslide and slope failure*

Figure 13 shows the detailed definitions of the tilting rate and time, where T_i is the time until failure or stabilization, and R_i is the tilting rate. When the slope failed, "time" means the time that elapsed from measurement until failure. Conversely, when failure did not occur, "time" means the time between measurement and stabilization.

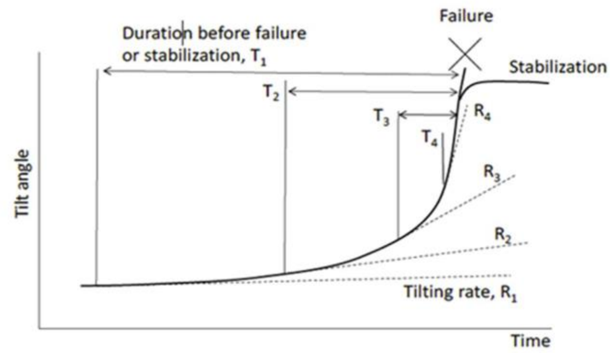

Figure 13. Definition of tilting rate and time remaining until failure.

Figure 14 summarizes the results of the authors' slope monitoring projects since 2004 to now, which have considered landslides, slope failure, collapse, and field experiments. The authors define landslides as events that require months or years until failure, slope failures as events that require days or weeks until failure, and collapses as events that only require hours until failure. Thus, the case of rainfall-induced slope failure is classified as a collapse. As previously mentioned, the brief amount of time until failure makes it difficult to select a relevant monitoring method. While the overall trend of the obtained data in Figure 14 is similar to the relationship between creep time remaining until failure and strain rate or minimum creep rate based on results of geomaterial testing of Saito's curve (Saito et al. 1961, 1965), it is further proposed that two different failure times may affect the plotted relationship.

In line with Equation 1, the authors approximate the data in Figure 14 using Equation 1.

$$\log_{10} t_r = 0.306 - 0.597\log_{10}\frac{da}{dt} \pm 0.6 \quad (1)$$

where t_r denotes the time remaining until failure (hours) and $d\alpha/dt$ denotes the rate of the tilting angle (degree/hour). The prediction using Equation 1 is indicated by the solid black line in Figure 14. To further improve the time prediction, the following measures are considered:

i. Classification of events according to their type, such as landslide, slope failure, collapse, and so on.
ii. Classification according to slope materials, such as weathered granite, sedimentary rocks, soil in natural slopes, and so on.
iii. Classification according to geology, geography, and geomorphology, such as steep slope, smooth terrain, and so on.
iv. Classification according to type of rainfall time history.

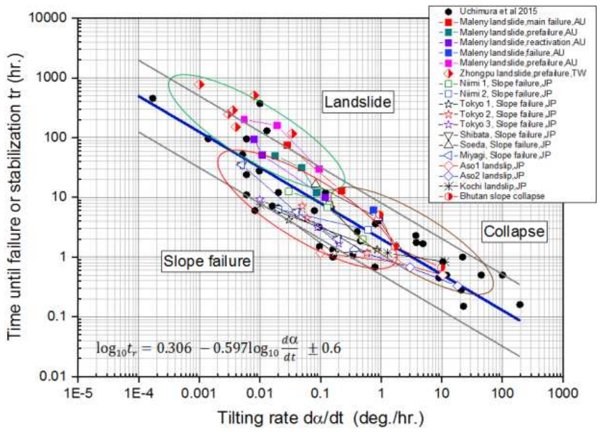

Figure 14. Relationship between time remaining until failure and tilting rate based on field monitoring.

To implement these measures, a more extensive case history is required. At this moment, the different slope displacement rates in Figure 14 suggest the following:

i. Landslides have sufficient time until failure, and emergency caution and warning alerts are appropriate measures.

ii. The failure of surface sediments (slope failure in Figure 14) has several hours until failure if a warning is issued when the rate is 0.1°/hour.

iii. Collapse occurs suddenly and practical experience suggests that failure occurs within one hour or less. Hence, evacuation is not feasible and the reinforcement of the slope in advance using rock bolts, and so on, is advisable.

3.2 *Early warning by using multi-point monitoring*

Wang et al. (2017) proposed an early warning method based on multi-sensor monitoring. Recently, the authors have extended the scope of slope monitoring to multi-point monitoring, which can capture both the spatial and temporal behaviour of the entire slope. Additionally, multi-point monitoring can avoid erroneous warnings caused by very local slope movement and animal contact, among other causes of error. Thus, the reliability of early warning is improved.

The spacing between multiple sensors must be kept within a reasonable limit (a few meters to a few tens of meters, as in the practical cases discussed in this paper), and a new index of slope movement has to be proposed in the place of a single sensor's tilting rate, as in past practical cases. Certainly, the new index has to handle data at all monitoring points. Presently, the new index is assumed to be expressed as follows:

$$V_{alarm} = \sum_{i=1}^{n} (|V_i| \, x \frac{A_i}{A} \, x \, a_i) \tag{2}$$

where n is the total number of tilt sensors; V_i is the tilting rate (otherwise denoted as dα/dt) in the slope direction of the ith sensor (°/hour); Ai is the area covered by the ith sensor; A is the area covered by the entire sensor array; ∂_i is the coefficient determined by the geology, geography, soil type, and vegetation conditions at the installation points. Moreover, the ∂_i coefficients regard the field conditions and their values are determined based on the results of geomaterial experiments and the assessment of geologists. Although this issue requires further investigation, ∂_i =1 is currently used in practical situations.

4 CONCLUSIONS

The authors have been developing slope failure monitoring and early warning technology. This technology is characterized by the use of MEMS tilt sensors. In earlier versions, monitoring was conducted using a single sensor. However, a multi-sensor approach was implemented in a recent development. This paper introduces the most recent development of the authors' EWS based on data obtained from several sites and their interpretation. The following conclusions were drawn from this study.

(1) In the previous version of the technology, a caution alert was issued when the tilting rate exceeded 0.01°/hour, while a warning associated with an evacuation order was issued when the rate exceeded 0.1°/hour. These threshold values are based on practical experience, and have been validated by recently obtained monitoring results.

(2) In this paper, various monitoring cases are summarized. The linear relationship between the logarithm of the rate of the tilting angle of the sensors and the logarithm of the time remaining until slope failure was demonstrated. This relationship has an interesting similarity to the relationships suggested by the Saito's rheological interpretation of laboratory soil tests.

(3) The recent extension of monitoring to multi-point practice enables a more a detailed interpretation of slope behaviour in the transient stage and up to the final failure.

5 ACKNOWLEDGEMENTS

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